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USRA WORKSHOP REPORT - ELECTROSTATIC FOG DISPERSAL

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Interim Report, Contract NAS8-33730

June 13, 1983

Prepared for

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16. ABSTRACT

The Workshop was held at the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, on February 1-2, 1983. The Workshop was attended by seventeen experts in the scientific fields of fog and cloud physics, charged-particle electrodynamics, atmospheric turbulence, atmospheric electricity, and electro-gasdynamics. The major objective of the Workshop was to assess the scientific merits and scientific basis of the proposed system and to assess its potential for operational application.

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USRA WORKSHOP

ELECTROSTATIC FOG DISPERSAL

Sponsored by NASA/MSFC
Boulder, Colorado
February 1, 2, 1983

THE WORKSHOP REPORT

Assembled and edited

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M. H. Davis, USRA

June 13, 1983

CONTENTS

INTRODUCTION

The Workshop met for one and one-half days at the National Center for Atmospheric Research (NCAR) in Boulder, Colorado. The National Aeronautics and Space Administration (NASA) representatives were Mr. Dennis Camp and Dr. Vernon Keller of the Atmospheric Sciences Division, Systems Dynamics Laboratory, Marshall Space Flight Center, Alabama (MSFC). The Workshop was attended by seventeen experts in the scientific fields of fog and cloud physics, charged particle electrodynamics, atmsopheric turbulence, atmospheric electricity, and electro-gasdynamics. Two observers from airline companies and one observer representing the FAA attended. The participants are listed at the end of this section. The Workshop was chaired by Dr. M. H. Davis of the Universities Space Research Association (USRA), who was assisted by Mr. John Masterson and Ms. Melanie Cook.

The Workshop report is divided into two parts. The first part, "The Workshop Report," gives an outline of the Workshop, followed by conclusions and recommendations. The second part, "Appendices to the Workshop Report," describes the proposed system of fog dispersal through charged particle jets and summarizes other proposals for warm fog dispersal. Some background scientific information is also included. Appendix C consists of material from the Workshop members.

OBJECTIVES OF THE WORKSHOP

Dennis Camp, NASA/MSFC

1) To review the current status of the ground-based charged particle fog dispersal program.

2) To assess the scientific merits and scientific basis of this proposed system.

3) To assess its potential for operational application.

4) To discuss what steps should be taken to demonstrate the scientific viability of the concept, assuming that it has viability.

5) To prepare a summary report based on workshop findings.

NASA/MSFC intends to base a decision on its future sponsorship of the charged particle jet concept for warm fog dispersal primarily on the results of this workshop. The results of the Workshop could also cause a redirection of NASA's efforts relative to warm fog dispersal.

Background Information

NASA's sponsorship of fog research goes back to the early 1960's. After early field tests, numerical modeling development was pursued by Marshall Space Flight Center during the 1970's. In the mid-70's, the FAA asked NASA to examine the charged particle jet concept. This led to a contract with FWG Associates of Tullahoma, Tennessee. During the first year of this contract a survey of warm fog dispersal methods was prepared covering many concepts including the charged particle jet technique. The FWG Study concentrated on this method since it was the focus of NASA interest.

In their 1981 report Frost and others discuss in detail the Panama Canal Zone Experiment that was carried out in Project Foggy by the Navy. The present Workshop discussed the results of this field experiment and concluded that they appeared discouraging, but were inconclusive.

FWG Associates have recently built and tested laboratory prototype charged particle generators to learn more of their characteristics. This effort was discussed at the Workshop by Walter Frost. A new Summary Report, dated February 1, 1983, was prepared especially for the Workshop and distributed to the Workshop participants.

1. PRESENT STATUS

W. Frost's Workshop presentation included:

1. Discussion of the need for warm fog dispersal: Annual losses to airlines due to operations at the eight most affected airports amount to at least $23 million.[1] Costs of delays and loss of ship transport through the Panama Canal amount to $40,000/transit.[2] Fog is a factor in about 15 percent of all fatal aircraft accidents.[3] [Significant improvements are being made in the technology of airline operations at major airports in the presence of reduced airport visibility. However fog clearing will unquestionably remain an important issue for many years to come.]

2. Review of Airport Visibility Criteria: Cat-I, Cat-II.

3. Review of proposed electrical fog dispersal methods.

4. Review of the charged particle jet method: its physical principles [which are still poorly defined]; its projected advantages: relatively low initial, operating, and maintenance costs; lack of air pollution.

5. Discussion of the present status of the prototype development of a small charged particle generator.

6. Outline of a proposed field test using an array of charged particle generators.

<u>Comments</u>

Background analysis of the physics of the proposed method is still incomplete. Without this, evaluation of the feasibility of the concept is impossible.

Further prototype jet charged particle generator development and testing is needed for optimization. Measurements are needed of the charge, size, and number density of the charged particles as they exit the jet, and as a function of height and location in the plume, along with measurements of current and electric field. In addition, extensive measurements are needed of the fluid mechanics of the plume, its interaction with the surrounding air, associated turbulence, entrainment, and the influence of wind. [Charged particle loading may significantly modify the plume. The validity of scaling concepts must be carefully evaluated and tested.]

Other electrical fog dispersal methods that are worthy of consideration include: Loos' variation, which is outlined in his unpublished Draft Report and was briefly presented and discussed at the Workshop; Ruhnke's proposal, which makes use of entrainment of the fog-bearing air into the jet plume; and the charged drop spray concept suggested during the Workshop by Latham.

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[1] NASA Contractor Report CR-3255 (1980).
[2] Personal Communication by Mr. Rhodes of the Panama Canal Commission.
[3] National Transportion Board Safety Study, NTSB-AAS-74-2.

2. THE SCIENTIFIC MERIT OF THE CHARGED PARTICLE-JET SYSTEM

It is not possible in a workshop context to adequately address the issue of the scientific merit of a complex proposal unless all of the relevant scientific questions relating to it can be answered. This is definitely not the case for the charged particle jet system. Lacking much important information, the best that the Workshop could do was to give an appraisal based on experience and best judgement, and then point out the areas where more information must be obtained in order for an adequate, informed assessment to be made.

If there had been a vote, based on the discussion and the written material it would probably have gone as follows:

[The idea, or some variation, definitely has scientific merit]... 3

[The idea *may* have scientific merit; continue study]............11

[The idea has no merit; support should cease].................... 2

Based on this appraisal, the consensus was:

> **NASA/MSFC should continue to sponsor the study of the charged particle jet system with the goal of acquiring the information needed to permit a definitive decision on its merits to be made in one year. The continuing study should be carried out by a Select Panel (see Section 4).**

Scientific and technical questions that must be answered

1. What are the details of the mechanism being proposed for fog clearing by the charged particle jet method?

Many Workshop participants indicated that they felt that the most scientific issue to be addressed was clarification of the physical mechanisms that the proponents of the method believe will act to clear the fog. [Loos has partially achieved this goal in his Draft Report.]

2. What is the mobility of the charged droplets ("seeds") when they emerge from the jet and as a function of height in the plume?

The mobility, k, depends upon droplet charge and size [as (q/a) for Stokesian particles]. For survival within the jet plume, k needs to be small, while for effective charging of the fog droplets and reasonable clearing times, k must be large. The mobility of fog droplets after charging is limited approximately to the seed mobility. Moreover, the time constant for charging depends on k as 1/k. Values for attainable seed mobility were quoted in the range 10^{-8} to 10^{-7} (m/sec)/(v/m). Seed droplet size and charge must be *measured*. The estimates based on other measurements are inadequate; there are too many unknown factors to allow for satisfactory modeling or scaling.

3. Will the droplets evaporate after their formation within the jet nozzle?

This question arises because the drops are supposedly formed in the nozzle by homogeneous nucleation. After exit into the plume, they enter an air mass whose supersaturation is extremely close to unity and the Kelvin curvature effect can be expected to bring about evaporation. On the other hand, their charge will act to stabilize them. If the drops evaporate, the result might be a stable cluster of ions. Further analysis is required, possibly along with laboratory experiments.

4. Will the charged droplets ("seeds") be carried aloft to the top of the fog layer by the momentum of the jet and turbulent transport? What is the effect of electrical forces?

The details of the process need to be clarified. To answer this question will require detailed analysis of the fluid mechanics of the jet plume, its interaction with the air mass, and the effect of turbulence. Electrical loading must be taken into account as well as electrical forces on the charged seed particles. A limited field experiment or tests within a chamber will very likely be required. The effect of wind needs to be investigated, since wind will cause the jet plume to bend over and change its geometry and dynamics.

5. What is the <u>maximum electric field strength</u> at the ground that can be used?

This is a <u>crucial</u> question, since the time-constant for clearing depends on the field strength, E, as 1/E.

Values quoted during the Workshop for the maximum field strength at the ground before a corona discharge would occur ranged from a few kv/m to near 1000 kv/m. (The maximum electric field under a thundercloud is a few 10's of kv/m.)

6. What will happen if corona does occur in the layer closest to the ground?

For this question and (5) the presence of fog must be taken into account, since it will modify the charge-carriers in the air.

7. Will the electric charging of the fog droplets proceed as predicted? Which mechanism of clearing dominates, electric precipitation or collection? Will the charging time constant have a reasonable value?

It may be possible to develop the answers to these questions through careful modeling of the process.

8. Will the seed droplets be distributed throughout the fog as required?

Analysis of the plume flow and turbulence is required.

9. What is the effect of the size distribution of the fog droplets, and the non-uniformity of natural fogs?

Modeling, including data on the variability of natural fogs, will be necessary.

10. If fog drops are swept out, will the clearing last?

A radiation fog once cleared will probably stay clear, so long as new fog-bearing air is not brought in through turbulent transport, or by weak local circulations. However, for advection and radiation-advection fogs, the possibility that the supersaturation will rise after the drops are swept out, and the fog will reform. This matter should be amenable to study through numerical modeling.

11. How rapidly, and under what conditions is new fog-bearing air transported into the cleared volume through turbulence and advection?

Answer using data on conditions in natural fogs, together with modeling.

3. THE POTENTIAL FOR OPERATIONAL APPLICATION

Many of the Workshop participants cautioned not to rush into a large-scale field test program or a demonstration before the physical principles of the system are much better understood.

Regarding the operational application of the system, if it proves to be viable, it is not necessary to demand that the system clear all fog under every possible condition. It would be valuable to aviation to be able to increase visibility, even if Cat-I conditions already exist. More generally, the system would have value if it would work only in cases with moderate wind speeds, wind directions near the runway direction, fogs of moderate density. The fog does not have to be completely dissipated if the RVR (Runway Visual Range) can be significantly increased.

There are important questions regarding aircraft safety. The highly charged seeds and droplets may produce radio noise, which could interfere with communications and navigational equipment. If the electric field strength at the ground is large enough to produce electric discharge phenomena, this could be a hazard to aircraft operations and ground equipment.

An advantage to the charged particle jet technique is that it is non-polluting (in contrast to thermal methods). Its cost has been estimated as being well below costs of the thermal system, though the Workshop was skeptical that the stated cost estimates were realistic.

The potential for operational use depends a great deal on the clearing time. If the time required for significant clearing is too long, then the system becomes impractical.

4. RECOMMENDED ACTION

There should not be a large field test or "demonstration" of the system at this time.

The first priority should be to form a Select Panel of experts with funding to carry out the required coordinated investigations. A single individual should be responsible for each part of the effort. The immediate objective is to answer the questions listed in Section 2 and thus to permit the feasibility of the proposed warm-fog dispersal system to be properly assessed.

The Select Panel will need members and consultants expert in electrogasdynamics, cloud physics, turbulence, atmospheric electricity, mathematical modeling, and field research techniques and management. The Panel should not only consider the charged particle jet method of fog dispersal, but also examine the merits of variations and other possible electrical techniques.

It should be possible to carry out the entire effort with a Panel of about six members, augmented as needed by consultants, that would meet four times in one year. The results of the study by the Panel should be critically evaluated by a group of experts: privately, by commissioning reviews. Finally, a workshop should be convened to make recommendations to NASA.

Suggestions for Panel membership. [Agreement to serve on such a panel is not implied.]

Cloud Physics: J. Jiusto
Analysis: H. Loos
Charging Mechanisms: J. Latham
Atmospheric Electricity: L. Ruhnke
Generator Development: M. Gourdine, W. Frost
Modeling: M. Plooster (Denver Research Institute)

The Workshop strongly recommended that H. Loos be funded to complete and publish his Draft Report on electrical fog dispersal methods.

5. A POSSIBLE DEVELOPMENT PROGRAM

The Select Panel should set the program for development of the electrostatic fog dispersal concept. However, as an example of how the program might proceed, the following steps might be considered. These are arranged in logical sequence -- much of the analysis and modeling could be carried out simultaneously. Data from field experiments are needed to answer a number of important questions, and the experiments should be carefully designed and carried out in conjunction with adequate theoretical analysis. Given an intensive and well-planned effort, it may be possible to carry out the program in about one year.

1) Further theoretical analysis of all aspects of the proposed system and its variations.

2) Numerical modeling using computer fog/cloud models.

3) Laboratory and limited carefully controlled field studies of seed dispersal and charging mechanisms.

4) Tests to determine the maximum field strength at the ground that can be used.

5) Further development of the prototype jet charge generator.

6) Measurements of the full set of parameters of the jet charge generator performance including current, flux of charged particles, radius, charge, both at the jet and as a function of height above the jet; jet plume flow parameters; effect of electrical loading; turbulence, entrainment, interaction with the surrounding airmass; effect of wind.

7) Analysis of field experiment configuration.

8) Tests within a large chamber and/or in a well-instrumented protected outdoor location.

9) Small-scale field tests with the objective, not of clearing fog, but of testing the concept using adequately calibrated sensing instruments.

At all stages of this development there must be coordination between theoretical and modeling work and experimental testing. The objective throughout the program development should be to obtain the physical parameters and design information that presently is lacking. The program must be configured such that it proceeds to the next step only if the results to that point appear favorable. Experience has shown that optimistic laboratory and modeling results are frequently not verified in the field. Fogs in the outdoors in real situations exhibit large variability in space and time, and from one instance to another. Moreover, Nature invariably provides unexpected difficulties and influences. The results must appear favorable indeed before the decision is made to carry out a full-scale field test or demonstration.

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USRA WORKSHOP

ELECTROSTATIC FOG DISPERSAL

Sponsored by NASA/MSFC
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APPENDICES

TO

THE WORKSHOP REPORT

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APPENDIX A

DISCUSSION OF CONCEPTS FOR WARM FOG CLEARING

Unlike the situation for supercooled fogs, there are no colloidal instabilities or "free energy" sources that can be exploited for warm fog dispersal. One concept would be to lower the supersaturation of water-vapor within the fog, thereby causing the fog droplets to evaporate (see the brief discussion below). The other concept is to remove the fog droplets by electrical sweepout.

This Workshop concentrated attention on the electrical fog clearing concepts, and particularly on the charged particle-jet method under development by FWG Associates under NASA contract. This has been variously referred to as ElectroGasDynamic or EGD (by Gourdine), as the Ruhnke-Gourdine method (by Loos), and by simply the "Charged Particle Technique," which is ambiguous. The term chosen for this report is "charged particle-jet". The basic principles of this method will first be discussed, followed by a more general discussion of warm fog dispersal concepts.

The Charged Particle-Jet Method of Gourdine and Frost

A comprehensive discussion of this method appears in the FWG Reports sponsored by NASA/MSFC.

An array of space-charge generators is located upwind of the area to be cleared of fog. [Several of the panel members felt strongly that the word "gun" should be avoided.] Within the generator, moisture-laden air is blown upwards through a nozzle. Droplets nucleate and are blown through an electric corona discharge. The resulting positively charged "seeds" exit in the high speed jet plume that emerges from the generator. The seeds are carried aloft and downwind in the plume by means of mass flow and turbulent transport. Possibly electrical forces play a role. The seeds are distributed within the fog layer to be cleared (30 - 50 m above the ground) and mix with it. Besides aerodynamic drag, the seeds are acted on by electrical forces: mutual repulsion, repulsion from the center-of-charge of the space-charge cloud emerging from the generator, and attraction to their images in the conducting Earth.

The space-charge layer aloft produced by the seeds acts as the source of an intense electric field E between that layer and the conducting Earth. The seeds move downwards in field E, encounter fog droplets, and are captured. In this way, fog droplets become charged and thus become sources for the field. The charged fog droplets are forced downwards by the field, and pick up neutral fog droplets in their path to the Earth. (A good deal of discussion has taken place about the relative importance of "electric precipitation", the removal of charged fog droplets through being forced downwards by electric field; and "collection removal", the action of charged fog droplets as sweepers, collectors of other droplets. But both processes will occur and detailed analysis of fog clearing must take both into account.)

Other Concepts for Clearing Warm Fog

1) "Thermal-kinetic" -- heat the airmass by heaters.

2) Seed with a material such as carbon-black to make the fog droplets absorb sunlight. [See the Arthur D. Little 1956 Report.]

3) Seed the fog with a hygroscopic material, thereby removing water-vapor.

4 Mix in dry air aloft by helicopter downwash.

Method (1), the thermal kinetic technique, is "probably the best method that exists today." It has been tested extensively and is in operational use in France (the Turboclair system.) Although very expensive to install and also to power, such a system might be cost effective in Los Angeles and perhaps in a few other airports in the U.S. Since it uses jet engines to generate the required airmass heating, it pollutes the environment with jet-exhaust products.

Method (2) has apparently not been extensively explored, though it might have promise during daylight hours.

Method (3) "looked pretty good on paper, but field results were a disappointment." [Comment at the Workshop].

Method (4) is discussed in the Christensen-Frost Report.

The electrical methods proposed for warm fog clearing depend, not on lowering the water-vapor supersaturation, but rather on removing the fog droplets. Several electrical methods have been suggested:

One [Ruhnke] is to "electrically process" fog-bearing air entrained into a vertical charge-carrying jet plume. [Loos pointed out that this method may require power expenditures comparable with the thermal-kinetic method, though it would have the advantage of not introducing fuel-combustion pollutants into the air.]

Another idea, briefly discussed at the Meeting by Latham would be to collect fog drops by highly charged "collector drops" that are sprayed into the fog.

Other electrical methods rely on the creation of a large vertical electric field in the fog region and causing the fog droplets to become electrically charged so that they are then swept out by the electric field -- collecting some of their uncharged fellows in the process.

The first problem is how to establish the required high electric field throughout the fog volume. A possible method might be to use wires carrying a high d.c. voltage mounted on high towers. Ions would be formed in the surrounding air, which might be adequate charge carriers. [Phillips] (A somewhat similar concept is discussed in the Arthur D. Little Company Report.)

It also might be possible in principle to mount space charge generators (charged droplet airjets) at the top of towers, so that charge could be injected directly into the top of the fog layer to be cleared. However, this would have obvious drawback of requiring an array of massive high towers to carry the generators together with associated power and water lines.

Locating the charged particle generators at ground level would be much more practical provided the charges can then be transported aloft. This is the concept of the Charged Particle-Jet method that forms the principal subject of this report.

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APPENDIX B

SOME TECHNICAL NOTES

PROPERTIES OF WARM FOG

By "warm fog" is meant fog that is above $0^{o}C$. Since warm fog does not contain supercooled water, it cannot be dispersed by seeding with agents such as dry ice or AgI, as can supercooled fogs. (By "fog" in the present discussion, "warm fog" is always implied.)

The elements needed to form a fog of water droplets are: available water-vapor, aerosol condensation nuclei, and the condition of water-vapor supersaturation. As a parcel of air cools and water-vapor saturation is approached, first water vapor condenses in a reversible way on nuclei to form haze particles. Then, if supersaturation is reached and exceeded, typically only by a few hundredths of a percent, haze particles activate to form stable droplets which grow rapidly so long as supersaturation is maintained.

In some fogs the condition of supersaturation is brought about by radiative cooling; in others, by horizontal advection, turbulent diffusion, and adiabatic cooling. Mixed situations are common. The droplet size distribution in natural fogs is often broad, extending from 0.5 to 40 micron radius. Droplet sizes are typically smaller for radiation fogs (2 - 15 micron radius) than for advection fogs (5 - 40 micron radius). Droplets, even the larger ones that have fall speeds in still air near 0.1 m/sec, can be temporarily suspended by turbulent eddies.

Fogs are characterized by relatively low liquid water content (LWC) (a few tenths of a gram/m^3), and small number concentrations (tens to a few hundreds per cm^3, if droplets with radii less than 0.1 micron are disregarded). LWC > 0.2 g/m^3 characterizes a <u>dense fog</u>. The physical properties of natural fogs show great variability both in space and time. Some of this variability is illustrated in the Figure on page B-2, from Garland (1971) which shows data on two fog samples. Both small and large drops contribute significantly to visibility degredation, as the Figure illustrates.

Fogs rarely occur under dead calm conditions. In radiation fogs, horizontal winds are typically 0.5 - 1.5 m/sec near the ground, and 1 - 3 m/sec at 25-50 meters. Wind speeds in advection fogs are roughly twice these values. Most advection fogs involve the passage of warm air over a cold moist surface, thereby producing sustained inversion conditions. Radiation fogs commence with very strong thermal stability. However, as dense fog develops, the level of net radiational cooling shifts to the fog top and, concurrently, heat flux from the ground beneath warms the base and very unstable lapse rates can develop. [from Jiusto's report]

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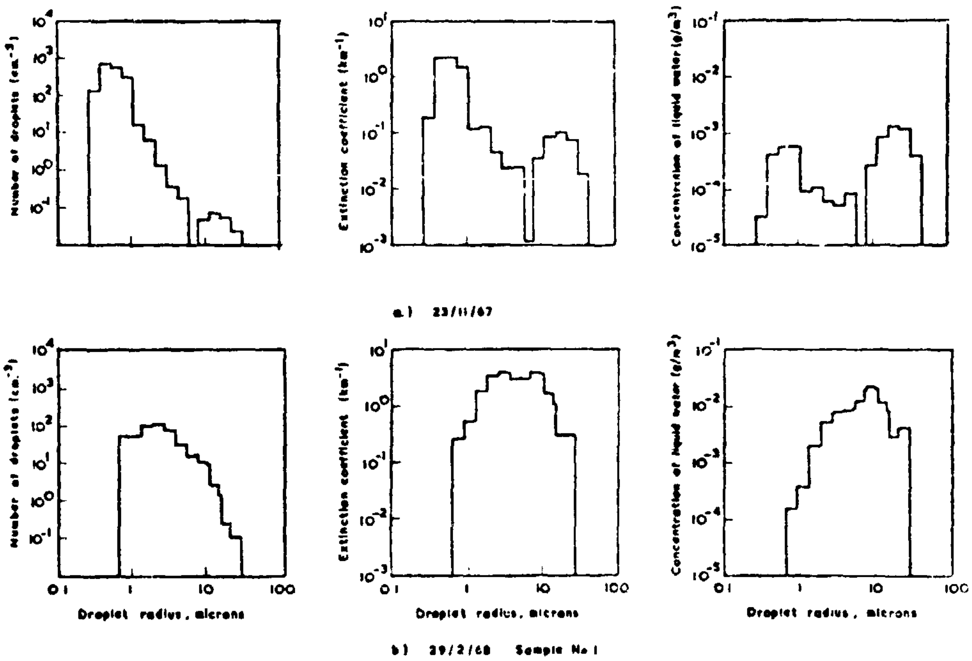

The contribution of droplets in various size intervals to the extinction coefficient and liquid water content of (a) a fog with numerous small droplets and (b) a fog with few small droplets.

FIGURE

Data on two fog samples showing natural variability and the contribution of droplets of various sizes to light extinction and liquid water content. (Garland, 1971)

CONCEPTS AND EQUATIONS

Visibility

An approximate formula for the visual range ("visibility") is:

$$V \approx (10^6)/(N\underline{a}^2)$$

where a^2 is mean square droplet radius in microns, N is the number density in cm^{-3}.

(Care must be taken in calculating the mean, taking into consideration the shape of the droplet size distribution; note the Figure on page B-2.)

There are two ways in principle to increase visibility in a fog: (1) by reducing the water-vapor saturation to near or below 100 percent, thereby causing droplets to evaporate (diminishing $\underline{a}$ and eventually N), and (2) by physically removing droplets from the fog.

Increasing the visibility will be called "clearing", with the understanding that it is a matter of degree, going all the way from increasing the visual range, V, to removing the fog completely. Fog clearing is a statistical process, involving large numbers of droplets. If the fog is completely cleared eventually,

$$V = V_o \exp(t/T)$$

where V_o is the initial visibility and T is the clearing time constant.

More generally, if the fog is partially cleared, and $b = V_o/V_f$, the ratio of the initial to final visibility,

$$V = V_o/[b+(1-b)\exp(-t/T)].$$

But it should be kept in mind that a natural fog often is extremely inhomogeneous and so the equation is only suggestive. It does not allow for inhomogeneities or changes in conditions during the clearing process.

Mobility

Mobility, k, is defined by the equation:

$$v = kE$$

where v is the velocity, and E is the field strength.

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For a Stokesian particle,

$$k \approx 0.5 \times 10^{-9}(q/a) \quad (m/sec)/(v/m)$$

where q is the charge in electronic charges, and a is the particle radius in microns.

[For ions $k \approx 10^{-4}q$ (m/sec)/(v/m)]

Clearing Time Constant

The time to achieve clearing can be estimated simply using the "slab model" of uniform charge density throughout the fog layer. If E is the mean field (around $E_{max}/2$) then the time in seconds that a droplet at the top of the layer takes to fall to the Earth under the influence of the electric field is about:

$$T_c \approx h/(kE),$$

where h is the height of the fog layer in m, k is drop mobility in m/sec per v/m, and E is the field in v/m.

For a workable system, clearing time constant T_c must be short enough so that significant clearing will occur in the time it takes the treated air mass to move from the Generator Array to the aircraft runway, and not so long that new fog moves into the cleared region. Times of a few hundred seconds appear to be all right. (The actual cut-off time depends upon local conditions and design considerations.)

Fog Droplet Charging

The time constant, T_q for fog droplet charging in the proposed method turns out to be about twice T_c. Droplet charging follows the law:

$$Q = Q_f(t/T_q)/(1+t/T_q).$$

where Q_f is the final charge acquired.

These concepts do not take into account the fact that the droplet charging and sweepout are coupled dynamic processes. However, separating the processes in most cases should allow satisfactory estimates to be made provided suitable averages are used.

CONSTRAINTS AND LIMITATIONS

There are several issues involved that are imposed by the physics and must be reckoned with in any analysis. (See Loos' Draft for a more complete discussion.)

(1) The field charging limit applies for droplets that are charged by "seeds" or ions under the influence of field E. Electrostatic theory shows that the charge the drop can acquire is limited:

$$Q_f \leq 3\ a^2E \quad \text{(e.s.u.)}$$

When this limit is reached, no further electric lines of force terminate on the back side of the drop, so the seeds (whose inertia is ignored in this analysis) are swept past in the airstream.

(2) The Wilson Velocity Limit states that since charged seeds (or ions) need to catch up with fog droplets to be captured (front capture is unimportant), they cannot charge the fog droplet to such a degree that it moves faster then they do in field E. Moreover, as the fog droplet picks up charge, the charging rate diminishes.

(3) The Source Constraint arises because after the initial ch rging stage of fog droplets by seeds, the electric field is produced by the same charged fog droplets that ultimately are swept away by the field. [The Source Constraint depends upon the details of the fog dispersal method; see Loos' Draft.]

(4) The Maximum Field-Strength Constraint. A key issue is that of the maximum electric field at the ground that can be tolerated. The field strength clearly cannot exceed electrical breakdown values. It should not exceed values where corona discharges occur, because of aircraft safety implications. The maximum field strength at the ground that can be used as a design criterion was a matter of debate during the Workshop with no concensus. Estimates ranged from about 10 kv/m to 500 kv/m. (Maximum thunderstorm fields are of the magnitude 100 kv/m.)

(5) The Seed Mobility Dilemma. Seeds charged in the Charge Generators, must be carried aloft to the top of the fog layer to be cleared. Their mobility needs to be low enough so that they will not be expelled from the jet plume by electrostatic forces. However, because of the Wilson Velocity Constraint, which says that the velocity of the charged fog drops cannot exceed the seed velocity in the electric field, rapid fog clearing implies a need for high mobility. [The dilemma can possibly be circumvented, see Loos' Draft.]

LOOS' VARIATION

Loos has carried out a detailed analysis of the charged particle-jet fog dispersal method in an effort to find ways to circumvent its limitations. He concludes that a variation has promise. His scheme involves using a gapped line of generators, and release of negative high-mobility seeds at ground level. He explicitly considers the cavity formed between the charge-carrying jet and the ground as the jet is bent over by the prevailing wind. These ideas were mentioned only briefly at the Workshop and are discussed in more detail in Loos' Draft Report.

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APPENDIX C

ADAPTED FROM MATERIAL SUPPLIED BY PANEL MEMBERS

This Appendix consists of statements adapted from written comments from individual panel members together with notes based on the Workshop discussion. These statements have been reviewed and approved by the panel members. Hendricus Loos and James Jiusto supplied more formal reports which appear verbatim.

CONTENTS

1. Adapted from notes and Workshop discussion by Marx Brook

1. The huge electric fields suggested will surely give rise to corona at the ground. The limit may be around 10 kv/m (the limit depends upon the character of the ground: whether it is wet, whether it has sharp points or a rough texture, etc.) This issue needs to be investigated and clarified.

2. It is important to measure the mobility of seed particles from the charged particle generators. A single jet should be adequate for such measurements.

3. Nature has a way of providing surprises, no matter what we do. Once the seeding charges are released, we cannot control what happens. Things never work in the field as simplified model calculations would suggest. We need to be careful to adopt a realistic approach to the problem.

4. Suggested research directions

a) There needs to be a clear and consise statement of the method being proposed, and a detailed analysis needs to be made taking into account as much of the physics as possible (perhaps by H. Loos.)

b) The hardware development should be continued at a moderate level of funding, with emphasis on measurement of all the parameters associated with the charged particles, and their transport aloft. We need to know the charges, mobilities, and concentrations as a function of height.

5. Statement advising measured development

It is important not to rush into a field experiment unless a detailed analysis and small-scale experiments under ideal conditions give results that are very encouraging. The importance of warm fog clearing is evident, but must not be allowed to generate the sort of impatience to "get on with it" that led to the weather modification fiasco.

5. A valuable reference

In 1956 Arthur D. Little, Inc. published a report to the Signal Corps "Warm Fog and Stratus Cloud Dissipation" that gives a valuable analysis of the problem along with several other interesting suggestions for fog clearing techniques. [These include fog seeding using a bipolar charge distribution, use of high wires carrying a high-voltage d-c potential, and use of an light-absorbing smoke to increase the absorption of sunlight by fog droplets.] They report some preliminary field-test results.

6. The term "gun" has become widely used for the jet charged particle generator. It is an unfortunate usage and should be avoided.

2. Considerations for Aviation Adapted from notes by Albert Brown

The fog characteristics relevant to aviation are:

Fog density - measured in "RVR" Runway Visual Range -- the horizontal distance along the runway that a pilot can see lights.

Fog duration -(typically several hours).

Minimum visibility for landing by most aircraft and most pilots at major airports is 200 foot ceiling (65 m) and 1/2 mile (800 m) horizontal visibility (known as "200 & 1/2"). Operation under these conditions is Cat-I (for "Category I"). A much smaller number of aircraft and pilots can land at a smaller subset of airports under Cat-II conditions (minimum RVR of 1200 feet, or 400 m). An important point is that many airports, aircraft, and pilots are not qualified for CAT-I operations, so even improvement of visibility in fogs with 2400 RVR would be of value.

[Note that RVR is not a meteorological quantity, it depends upon the ability to see lights, and so is airport dependent. For a sketch of the Cat-I and Cat-II regions for LAX, see the FWG Assoc. Feb. 1, 1983 Report.]

A system which could improve visibility in the "relatively easy" cases of low wind speed, wind direction near runway direction, and relatively light fog would still be of importance to aviation. The ability to increase 900 RVR to 1/2 mile, for cases of wind directions within 30^{o} of the runway and wind speed <3 knots would take care of perhaps 85 per cent of airport fog situations. It is not necessary to solve the problem of dispersal of very dense fogs (300 ft RVR or less), high winds (>4 knots) or wind direction perpendicular to the runway, in order to be useful.

3. Adapted from notes by William Cotton

1. Radiation fog
For a pure radiation fog, removal of fog droplets will reduce the radiative flux divergence at fog-top, since radiative heat loss is proportional to the integrated liquid water content through the fog depth. For this case initial clearing mav result in complete elimination of the fog except for filling in by turbulent diffusion.

2. Advection fog
In the case of advective or radiative-advective fog, radiative cooling is not likely to be dominant. Instead, advection and turbulent transport dominate the production of supersaturation, S. When liquid water is removed, supersaturation will rise. If (S-1) rises sufficiently (perhaps only 0.05%) un-activated haze particles may be activated, forming cloud droplets and bringing the fog droplet population back to near original levels.

3. Even if the aerosol/haze particles are not activated, they will swell in size due to rising supersaturations. There is some evidence (Hindman at CSU) that the swelled haze particles cause optical extinction nearly as effectively as fog droplets.

4. What is needed is a model that includes the aerosol/fog droplet distribution along with the fog formatative/dissipative processes: radiation, turbulence, advection -- particle removal through electrical precipitation sweep-out.

5. Another concern is that the proposed fog clearing method adds water to the fog. This should be modeled to determine the consequences. [Gourdine emphasized that the generators should be configured to use a minimum of water.]

6. In summary, the proposed concept for fog dispersal shows promise, but much more theoretical and experimental clarification is required before it can be fully evaluated.

4. Adapted from the statement submitted by Meredith Courdine together with the Workshop discussion

The Panama Canal Zone tests would have had the potential of verifying the electrogasdynamic method, had there been better test equipment and a better site. A review of the results of that test and the field and laboratory tests preceeding it leads to the conclusion that there was a satisfactory methematical model at that time and many of its salient features were verified. There were only 16 generators, but there was evidence for uniform charge distribution to heights of 100 ft due to turbulent mixing.

The electric field generated was measured using a hand held field meter and found to be 4×10^4 v/m at the center of the array; a factor of 10 larger near the generators. The measurements were at night on a wet grassy field and there was no visual evidence of corona. An explanation: low mobility charged particles may quickly attach any high mobility electrons or ions present and thus prevent electrical breakdown due to the avalance effect. Near sharp points the field will be amplified and local breakdown in the air may occur, but note that the field decreases in strength with altitude and breakdown can only occur close to the ground.

The fog chamber tests by Jiusto at SUNY showed that the rate of fog precipitation was exponential. The seed mobility was calculated using the measured time constant to be 10^{-7} m/sec per v/m. Results obtained using a chamber are difficult to interpret because of wall effects.

A new field experiment should be carried out using a multiplicity of generators. Energy Innovations, Inc. has the experience to design charged particle generators for field application. A much better job can now be done of site selection and test design than was done for the Panama Canal Zone tests.

[In his blackboard presentation, Gourdine showed that the time constant for clearing can be written approximately:

$$T \approx h/(kE)$$

where h is the height in m, E the field strength in v, and k the mobility in (m/s)/(v/m).

The equation is based on the assumption that the fog droplet mobility has reached its limiting value based upon charging by the charged seeds.]

5. Adapted from notes supplied by Warren Kocmond

1. Research Questions:

a) The issues of the maximum field strength and,
b) the expected mobility of the charged particles from generators must be resolved before progress can be made.

c) The ability of the charged particle jets to deliver charged seeds to a height of 100 ft seems unlikely and needs to be verified.

d) Another pressing issue is to achieve a better understanding of the physical mechanisms that can be expected to operate to bring about fog clearing. Myron Plooster of Denver Research Institute has the computational models to contribute significantly to this effort.

2. Approach to testing the concept:

a) It would be very important to thoroughly test and evaluate a single space charge generator. Knowledge of parameters such as the drop size distribution, induced electric field, charge-carrier mobility are essential to evaluation of the concept.

b) However, a single generator probably would not provide much of a test of the overall process (for example, the height to which the charged particles would be carried, the time-constant for fog clearing, or the actual induced electric field produced). Therefore, tests with a minimum size array may be called for. The test should be designed to evaluate the mechanisms that are operative in the fog, by measurements of fog droplet parameters along with electrical parameters. But there should be no requirement that actual fog clearing take place. The objective would be to carry out the needed research, not to demonstrate a system.

3. Comments on a full-scale test plans.

A full-scale field demonstration is clearly not warranted at the present time. There is simply not enough known about the performance of the generators or the physical mechanisms that are operative such that results of a field experiment could be interpreted, whether they were positive or negative.

What is needed is a measured approach. One-generator tests could be carried out this spring or summer. Then, as data are gathered, modeling and design effort could also proceed with hopes of conducting a well-designed field test, with specific research goals, by summer or fall of 1984. At any stage this program could be redirected if results appeared to be negative.

6. Adapted irom notes supplied by Bruce Kunkel

"Back of the envelope" calculations in 1972 were not encouraging for fog clearing, even if the system could produce the charges and electric fields suggested. A few years later, a detailed analysis carried out by Paul Tag (who is at the Naval Environmental Protection Research Facility, Monterey, California) supported these negative conclusions.

A characteristic of models that deal with fog modification processes is that the simpler the model the more optimistic the results appear to be. The simple models showed great promise for hygroscopic seeding in fog dispersal. But as the models became more complex, and more realistic, the results became progressively more pessimistic. Even the simple models of the electric charge techniques are not very optimistic. No theoretical or experimental evidence was presented at the Workshop that leads to the conclusion that the charged particle technique is viable. It is therefore recommended that there be no further funding for developing this technique.

If NASA desides to continue funding, then more emphasis should be placed on modeling. The models should be used as an aid in defining the optimum generators, and in designing effective field tests. Data from the tests should be fed back into the models and an optimum design developed by iteration. Of course, before doing any field tests or further equipment development, the models must show that the concept has some reasonable probability of success.

The assertion that the system, if feasible, would be relatively cheap is almost certainly wrong. A central water system will surely be needed, the units will have to be centrally controlled, and they would have to be designed to withstand exposure to the elements for months at a time with minimum maintenance.

7. Statement supplied by John Latham (edited)

The problem of fog dispersal is difficult, because the physical situation is extremely complex, and because there are significant gaps in our knowledge of some of the fundamental processes involved.

I feel strongly that NASA should not proceed at this time to implement a major field experiment as proposed by Frost. It would be premature to do so. The experiment probably would not work (in the sense of clearing fog), it would not be optimized, and since the physical mechanisms have not been clearly delineated and analyzed, the results would be impossible to interpret in a meaningful way. On the basis of the evidence presented at the Workshop -- particularly the question of the time-constant, which appeared to be too long for a workable system -- the likelihood of success appears small. Indeed, there may be other methods for fog dispersal that offer advantages [such as the suggested technique of spraying in highly charged large drops to act as scavengers for the fog droplets.]

We must be conscious that weather modification provides a tragic example of an important issue ultimately being abandoned because huge amounts of support yielded no conclusive results from experiments that had not been carefully thought out, and were not based upon adequate understanding of the physical processes involved.

On the other hand, I feel that it would be defeatist and wrong to abandon, at this stage, attempts to disperse fogs by electrical means. There is sufficient uncertainty in our current understanding that an effective system may be hidden within this basic concept, if only we are innovative, and can optimize our planning and design. The uncertainties and ideas could be explored and resolved within a limited time, and my suggestion is that such a process be implemented immediately.

Recommendation

I would advocate the establishment of a small Panel of Experts, whose task would be to examine alternative schemes of electrostatic fog dispersal, to identify theoretical and technical questions which any promising scheme may reveal, and to take action with respect to resolving these questions. This could involve the performance of specific, limited field tests (to establish, for example, the charge and size of the particles produced by Frost's generator), surveys of information on particular questions (such as the maximum electric field that can exist over the terrain and areas relevant to fog dispersal), and theoretical/design studies such as the tracking of a simple mechanism of dispersal through each crucial stage. The Panel would not execute all of the work itself, but would procure the services of consultants. This procedure could lead in a period of less than one year to the definition of a fog-dispersion field experiment designed to test fully the favored mechanism or mechanisms if good prospects emerge.

The Panel would need members with expertise in: electrogasdynamics technology, cloud physics, atmospheric electricity, fluid mechanics, mathematical modeling, and field research. Dr. Jiusto would seem to be the ideal chairman; Dr. Loos' contributions would be of great importance; Dr. Frost's committment to the problem would make him a clear choice for membership; and perhaps 3 or 4 other people would be required. I suggest that the Panel meet perhaps four times in one year.

An alternative method of fog dispersal that might be considered is suggested by recent experiments by Michael Smith at the University of Manchester. He produced highly charged drops (some tenths of the Rayleigh bursting value), passed them through a cloud of water droplets appropriately sized for a fog, and measured collection efficiencies. The collection efficiencies approached the value 20, and his analysis showed that capture was due to dipole, not Coulomb, forces; so that neutral fog droplets were picked up. The original diameter of the charged drops was about 100 microns.

The method appears worthy of study. It would have a very short time constant for clearing (an estimate is 60 sec, using reasonable values). It would be best to use a bipolar charge distribution, thereby eliminating the problem of high electric fields. [The concept of using a spray of droplets carrying both + and - charges may seem unworkable. Wouldn't oppositely charged droplets simply collide and neutralize? In fact, the Coulomb force falls off rapidly, as $1/r^2$, so oppositely charged droplets can coexist in the same airmass. In nature droplets carrying charges of both signs are frequently found in the same air sample.]

8. Notes based on material supplied by John Minardi

The charged particle method of fog dispersal has definite scientific merit and that it should be pursued further. Frost, is basing his development on the Gourdine model. The Loos model and the Ruhnke models could also be studied using the same equipment. (Ruhnke's model, however, calls for a larger generator.)

Some mechanism, presumably turbulence, suspends fog droplets with terminal velocities as high as 0.2 m/sec. If we produce an electric field of 200 kv/m and fog drop mobilities of 10^{-6} (m/sec)/(v/m), we would obtain a drift velocity of 0.2 m/s which is just equal to the maximum terminal velocity of the larger fog droplets. For a downward drift velocity some of the fog may precipitate out. But if movement is up, as in Loos' model, then none of the fog will would be removed. If the mobility can be increased to 10^{-5}, or the electric field proportionately increased, and velocities of 2 m/sec could be obtained, then significant clearing may result.

On the other hand, the 0.2 m/sec drift velocity may be sufficient to produce a significant effect on radiation fog. It would appear that radiation fog under conditions of low winds represents a realistic first goal for warm fog dispersion by the charged particle method.

Concern was expressed at the Workshop that ground corona would occur at field strengths of 10 kv/m or less. It was suggested, however, that this corona would serve to charge nearby fog drops, which would then shield the ground from the high electric field and stop the corona. I believe that this shielding would occur and permit higher fields to be used. (This may explain the high field measurements reported by Gourdine in the Panama Canal Zone experiment.) These are important questions, since field strengths of at least 200 kv/m are required by the system.

On reviewing the Frost design of the particle generator, I believe that a substantial improvement can be achieved by redesign of the nozzle and needle configuration. The nozzle should be very short, and should be made of metal. Maurice Lawson of UDRI would have valuable advice to give on nozzle design.

Recommendations:

1) that a test program be undertaken based on the Gourdine model, but also to obtain information relative to Loos' and Ruhnke's ideas.

2) that early field tests be limited to a maximum of 16 generators, with later expansion to the 51 generator configuration proposed by Frost only if favorable results are obtained.

3) that field strengths at the ground in excess of 100 kv/m be demonstrated for various types of terrain.

4) that the particle generators be redesigned to improve performance.

5) that the issue of aircraft safety be assessed if favorable results are achieved.

9. Remarks based on an informal report by Sabert Oglesby

It should be noted from Dr. Frost's presentation that properties of the charged particles formed in the generator: charge, and size have not been measured. A major justification for the additional test program proposed by Frost would be to make these necessary measurements.

The concept of fog dispersal by charging the fog droplets by the "seeds" is analogous to particle charging in an electrostatic precipitator. The primary difference is that here the charging is brought about by interaction with particles rather than ions. Therefore, because of the lower mobility of the particles, charging rates will be significantly less than in a precipitator; charging times will be much longer.

The electric field is to be provided by the space charge produced by the seed particles and the charged fog droplets; it is greatest at the ground and decreases to zero at the top of the charged layer. If the field strength at the ground is limited to that under a thundercloud (quoted as 1×10^5 v/m), this would represent a severe constraint on the proposed fog dispersal system.

The major mechanism of the proposed method is precipitation of the charged fog particles. Since turbulent velocities may be higher than the electrical migration velocities, turbulence will dominate in all but a boundary layer next to the ground. Fog particles in the boundary layer would be collected, then turbulence would bring new particles into the boundary layer. This concept is similar to the collection process in electrostatic precipitation, and therefore the removal rate can be estimated to a reasonable approximation. A complication is that turbulence will not be confined to the area to be cleared -- additional fog will be brought into the area through turbulent transport. To be effective, the system will have to remove fog at a rate fast enough to achieve the desired visibility against this competing effect. [If the analogy to an electrostatic precipitator is the proper one to use, the implication is that it may be unnecessary to disperse the charged particles to the top of the layer to be cleared. In the precipitator model, all of the "clearing" will occur in the lowest layer near the ground.]

The Panama tests were discouraging, since although the desired electrical effects were apparently achieved, there was no convincing evidence that visibility was improved. In view of this result, another field test is not recommended unless analytical or laboratory studies show that the concept has feasibility.

Using the seed charges, and mobilities suggested during the Workshop, along with the maximum electric field strength at ground level under a thundercloud (100 kv/m), it appears that the charging time constant will be of the order 10^4 sec, which is excessive. This may be why the Panama Test failed to show positive results and it casts doubt on the entire concept.

10. Notes based on material supplied by Byron Phillips

Some problems associated with the proposed system:

1) Achieving proper mobility is a contradictory requirement, since low mobility charge-carriers are needed to get to altitude in the plume (jet), while high mobility charge-carriers are needed for effective charging of the fog droplets in reasonable times.

2) It may be difficult to provide adequate power to the plume to transport the charges and charge carrier media to sufficient height to be effective.

The large fields required will almost certainly produce a corona discharge at the ground which will first appear at sharp points. The result of this corona discharge will be to create negative ions, which then may attach to the lowest lying fog droplets. One effect will be to limit the field in the boundary layer nearest the ground. The issues of the maximum field strength that can be used, and the effect of corona at the ground need to be examined carefully.

An alternative electric fog dispersal method that might be considered would be to create a large electric field by means of high wires carried by masts charged to high voltage (+DC). Corona around the wires would create ions, which then would charge the fog droplets. A quick analysis of this idea indicates that it might have promise and be worthy of closer study. (The need for high towers might present difficulties near an airport. A similar idea is discussed in in the Arthur D. Little 1956 report, though they may not have used wires that were high enough off the ground to accomplish the purpose.)

11. Adapted from notes and discussion by Lothar Ruhnke

Points to be made:

1) The information available at this time is not adequate to permit an assessment of the value of the proposed system.

2) Evidence so far is that electric precipitation rather than sweep-out by coalescence would be the dominant mechanism.

3) The time constant for fog dispersal should be greater than 60 sec, but not longer than 600 sec.

4) Clearing to altitudes of 60 m is needed, but methods which clear to an altitude of even 10 m are still interesting enough to be pursued.

5) Tall structures cannot be tolerated near runways, but some surface modification in areas near the runway is acceptable.

6) The means by which charges and electric fields are established is by using a surface-mounted vertical jet in which air with unipolar charges are transmitted, first by the momentum of the jet, and subsequently assisted by turbulent fluxes of the external wind field.

7) Optimization of the concepts proposed by Gourdine, Frost, Ruhnke, and Loos suffer from contradictory requirements: high mobilities or the space charge in the fog are needed to improve decay time constants, but low mobilities are needed to effectively transport space charges into the fog.

8) It may be possible to alleviate some of the corona problem by using a corona guard near the jet generators, where the field is greatest. [This was a point brought up during the Workshop. The idea would be to create a very smooth surface that would allow very high field strengths without producing corona. The surface would have to be maintained clean and smooth. If a liquid surface were used, it would have to be quiet, without bubbles or dirt.]

9) The subject area requires knowledge and strong interaction of several different scientific disciplines: fog physics, boundary layer dynamics, dynamics of a turbulent jet, atmospheric electricity, airborne particle measurements, analytical physics, engineering and project management.

10) A consensus exists among most Workshop participants that the goal of any further experimentation should be to understand the physical mechanisms of the interaction of a jet of charged particles (seeds) with fog, wind, and turbulence in a realistic outdoor environment. Measurements on a single jet of sufficient size would be adequate. It is premature to worry about visibility improvements, or operational capabilities.

11) The proper size of the outdoor experimental jet is determined by the need to measure in an outdoor experiment, flow, electrical and microphysical variables, within the jet as well as in the area where wind and external turbulence have become dominant. Experience shows

that it is necessary to have at least 1000 cfm and near-sonic velocities at the orifice, although 10,000 cfm would be preferable. The charge generator should be adjustable in flow rate, charge density, and size and number of "seeds". Measurements in and above the jet at a minimum must include seed size distribution, fog size distribution, convection current density, jet and wind flow velocities, space charge concentrations, mobility of seeds and fog droplets, surface electric fields, occurrence of corona, liquid water content in the fog, and light scattering coefficients.

NASA should include by contract the following groups:

M. Gourdine - for construction of jets
J. Jiusto - fog microphysics
L. Ruhnke - atmospheric electricity
H. Loos - modeling and analysis
J. Latham - analysis of charge transfer mechanism

(One-year efforts at a funding level of about $40K each, not counting hardware costs.)

Note: During the Workshop, Dr. Ruhnke made a brief presentation of an alternative method of electrical fog dispersal which uses a jet charged particle generator, but processes the fog-bearing air through entrainment into the jet plume. This variation was only briefly discussed. Several panel members indicated that it should be considered as a possible alternative. Loos estimated that it could require an energy consumption near that for the thermal fog-dispersal method.

12. Notes based on an informal report supplied by William Scott

Overall impression: there is hope, but it is not possible to assess the feasibility of the proposed system, based on what is known at present.

Specific points:

1. A partial goal, clearing in 40% to 90% of cases, with time constants longer than optimum, would still be of value. Even a system as costly as the French thermal system, but non-polluting, would be worth considering.

2. For the next steps, each part of the program needs the guidance of a **single individual**, who would bring in collaborators, but would have primary responsibility. Reasonable choices would be: H. Loos for analysis and design of a scientific field program (together with W. Frost); J. Jiusto for further modeling. There should be close collaboration and interaction between scientific field tests and analytical modeling. Field tests of fog clearing may turn out to be important sources of scientific data, providing the tests are carried out carefully in close relationship with modeling and analysis programs, and measurement instrumentation is properly calibrated.

3. Specific Topics:

a) Seed mobility-enhancement through coalescence

There needs to be further study of charged droplet coalescence within the particle generator. Does such coalescence enhance mobility? Going from charge q and radius a to charge nq and radius $an^{1/3}$ would appear to multiply k by $n^{2/3}$. What about the effect of relative humidity throughout the path of the charged seed? (i.e. will the charged droplets evaporate before reaching altitude? And if they do evaporate completely or partially, what will be the effect on the system?)

b) The time for seeds to get up to predicted speed $v = kE$ needs to be estimated. Knowledge of electrostatic scrubber performance should be of value.

c) Concepts both of up and down fog clearance need more modeling. The effect of mixtures of seed sizes and of a spectrum of fog droplet sizes must be considered. The effect of turbulence which acts to hold the fog in place must be carefully modeled.

d) More use needs to be made of known fog properties and dynamics. Ranges of rates of advection, turbulent transport, and degrees of "lumpiness" in fogs need to be estimated and incorporated into models.

4. H. Loos needs support to publish a refined and shortened version of his report. Support for his further work is one of the best ways to spend money now. This must include the opportunity for Loos to call in consultants such as Latham, Brook, Gourdine, Ruhnke, and Jiusto.

5. Assessment of Loos' advanced ideas involving the jet canopy and

the gapped-jet principle need to be analyzed using fluid dynamics concepts. The whole concept must be adequately modeled.

6. More work needs to be done on the question of corona at ground level.

7. Field tests should be made to confirm that fields of 100 kV/m and greater at the ground are possible.

8. Field testing is needed in order to establish the heights, mobilities, charge densities, and maximum field strengths obtainable with state-of-the-art generators. Possibly information from a single generator could be used. Fog sampling techniques need to be added to proposed field test programs. Attention needs to be given to site selection. Air fields presently equipped for fog observations, or locations in Pennsylvania and Virginia with frequent quiet fogs are possible candidates.

The dynamics of a line or an array of jets will be different from a single generator, although valuable information can be obtained from a single jet. Tests with arrays of jets are probably a necessary part of the program.

9. Assuming that the concept is viable, careful attention must be given to adapting it to the needs of aircraft operations. Where would it be located at airports?

10. Other Proposals. Ruhnke's entrainment proposal needs consideration by further modeling to allow a definite conclusion as to its feasibility and energy requirements. Latham's suggestion of injection of large highly charged particles also requires careful modeling to allow for assessment of feasibility.

11. Other important points

a) The effects of high electric fields on instrumented aircraft need to be assessed.

b) The scaling relations used in modeling jet behavior should be verified.

c) Smoke tests of jet entrainment should be considered.

d) Frost's new particle generator needs final testing.

e) The possibility of field experiments using a large hanger facility should be explored.

13. Based on informal remarks submitted by John Wyngaard

There was controversy at the Workshop on a number of important issues: the validity and conclusions to be drawn from the Panama Canal Zone experiment, and the maximum field strength at the ground are two examples. The issue of maximum field strength is critical to the entire concept and must be resolved.

Regarding the design of a field program: field programs are much more expensive and difficult to conduct than most people realize. Their design must be guided by theory and their results analyzed in the context of theory. In the present instance, the theory has not been well worked out. There is no clear conception of how the idea is supposed to work, or even if it will work at all. First priority must be given to carrying out a comprehensive study that deals with all the relevant physics in the context of the proposed designs. This could be commissioned and reviewed within six months to one year and would provide the needed scientific underpinnings for the program.

Specific Recommendations:

1. There should be **no** field program at present.

2. Instead, there should be a fundamental design study. This should include a critical analysis of the potential clearing mechanisms for the various candidate schemes, including time response, energy requirements, environmental impacts, and cost. It should also include a critical review of the jet fluid mechanics, including the turbulent dispersal of the seeding charge field.

3. As a part of this effort, existing airport fog/weather records should be reviewed to determine the benefits from less-than-perfect clearing performance (and to assess the effects of water release).

4. This design study should be critically evaluated by a group of experts: privately, by commisioning individual reviews, not through a workshop.

5. Finally, a workshop should be convened to evaluate the reviews and to make recommendations on how NASA should proceed further. If a field program is suggested, its design should be critically assessed. The micrometeorology needs to be very carefully done, as does the fog microphysics. If numerical or fluid modeling studies are recommended by the panel, their details also should be critically assessed.

14. Notes from the Workshop discussion and Statement by Hendricus Loos

Much can be accomplished in developing a system such as this through careful and innovative analysis . As problems arise, one can frequently "invent around them" by thinking of alternative possibilities. There are certain inherent constraints based on the physics, [field charging limit, Wilson velocity limit, source constraint discussed in Loos' Draft Report] but they can perhaps be circumvented, at least partially, through clever variations. The important thing is to tackle each problem as it comes along using suitable approximations and physical instinct. It is not necessary to become bogged down in the extreme complexity represented by a full mathematical representation. That would consist of highly nonlinear coupled equations that probably can't be solved. But broken into pieces, the problem becomes tractable. The DRAFT REPORT discusses many important issues from this basis.

While the Gourdine system appears to be too slow, many of its difficulties are circumvented through a variation using a gapped-jet configuration along with release of high-mobility negative seeds at ground level. The bending over of the jet plume in the prevailing wind creates a cavity within which the fog is dispersed electrostatically (fog droplets move upwards in this case). The details are complex, and have not been fully analyzed, but this variation appears promising. [Loos presented a brief account at the Workshop, and his variation is discussed in more detail in his Draft Report. This development could not be discussed fully during the Workshop, both because of its preliminary state of development, and because the thrust of the Workshop was on the Frost/Gourdine approach.]

STATEMENT ON ELECTROSTATIC FOG DISPERSAL

by Hendricus Loos

The Gourdine system considered by Frost works in principle, but is far too slow for meeting CAT II requirements, considering the rate at which new fog is brought into the clearing volume by wind and turbulence. However, the basic element of the Ruhnke-Gourdine method of electric fog dispersal, i.e., the use of airjets laden with electrified particles, appears to be of great value. A number of variations on the theme of Ruhnke and Gourdine have been proposed, and already one such variation (call it "A") appears capable of meeting CAT II requirements, at a small fraction of the power needed for the heating method of warm fog dispersal, and with negligible environmental impact, up to the question of radio noise. In regard to feasibility, economics, and interference with communications and navigation remain to be studied. The existence of variation "A" provides encouragement that an effective electric fog dispersal system is possible.

In view of the grossly inadequate speed of the Gourdine system, and the existence of a far superior variation, I recommend that the Gourdine system not be field test ... However, variation A should not be field tested either at the pre nt time. A number of us have further and other ideas, which al. may be seen as variations on the theme of Ruhnke and Gourdine. I believe it reasonable, within the time frame impressed upon us by Dennis Camp, to allow a year for a rather intense activity aimed at finding a suitable variation. We simply must give the people with ideas and competence in this area a chance to contribute. In order to safeguard NASA's objectives, a number of provisions should be attached to this activity. The effort should emphasize innovation and feasibility, and it should avoid going off on scientifically interesting tangents which have a poor ratio of feasibility clarification to cost. Along the same lines, wisdom and discipline should be exercised in choosing a distribution of funds and time expenditure on the various parts and aspects of the feasibility considerations and innovation. This is hard to do; when I started out in this business I blew half my funds on very fine numerical calculations of collisions between charged and neutral drops of a kind not available in the literature, only to find out from other considerations that, for cases of effective electric fog dispersal, the Stokes number of such collisions is so high that drop inertia forces the collisions to be nearly geometric (i.e., straight trajectories). Anyone seriously involved in feasibility study of a novel scheme lives in constant fear of overlooking a dominant aspect of the problem. To minimize this risk, there should be frequent and intensive interactions between the participating groups on a personal basis. We should check each other's considerations and calculations in a friendly but serious professional manner. At the end of this one-year activity, competing variations should be compared for physical, technological, and economic feasibility, and for environmental impact as well, and the best variation should be chosen for further development and field testing. I acknowledge that one year is a very short time to do the job, but I think that some of us can pull it off.

The activity discussed above may involve some simple experiments aimed at clarifying certain points of feasibility. In addition to these, I see the need for experiments to settle, in an approximate fashion suitable for feasibility considerations, questions which appear to beset nearly all variations of the Ruhnke-Gourdine method of electric fog dispersal. It seems sensible to split off these experiments and let them be done separately. In this category, two experiments come to mind: (1) radio noise, and (2) high-load low-mobility jets.

(1) Radio Noise

Spark discharges may occur between drops, even for bipolar variations aimed at keeping the electric field small. For the large field cases, there may in addition be ground corona and corona or sparks on equipment, although the latter should be avoided by proper design. There should be concern about the electromagnetic radiation from these discharges, in regard to interference with aviation communications and navigation, and as a source of more general electromagnetic pollution as well. Marx Brook and John Latham may know the literature on the subject and may have an opinion on the need for an exploratory experiment.

(2) High-Load Low-Mobility Jets

All variations of the Ruhnke-Gourdine method of electric fog dispersal involve turbulent jets laden with electrically charged particles ("seeds"); the jets are usually located at ground level, and they are subject to wind. Since fog must be cleared over an extensive length of runway, one needs at least a row of such jets. The feasibility of Ruhnke-Gourdine variations is affected strongly by the gross features of the jets interacting with the wind, ground, and each other, body forces on the air inside and outside of the jet due to electric forces on the seeds, and slippage of the seeds with respect to the local air for the high-mobility case. For a row of jets, most of the gross features of the interacting fluid mechanics and electricity are well understood and have been calculated in order of magnitude. However, there are some weak spots and it would be valuable to have these clarified by an experiment. For such an experiment to be acceptable in cost and time we must reduce the number of variable parameters. Furthermore, the experiment should be set up such that it clarifies the weak spots in our understanding needed for feasibility assessment and design. The experiment should be done in one year, concurrent with the activity discussed earlier, in order that the results can be used in the tail end of the feasibility studies, and for the selection of the best Ruhnke-Gourdine variation. Also, the relative importance of this experiment is such that it should use up only a modest fraction of the available funds. Considering all these aspects, I recommend an experiment with a single row of jets, using seeds with low mobility but a large current. The low mobility will eliminate slippage of the seeds with respect to the local air, thereby dramatically reducing the complexity of the physical situation. It also removes one parameter dimension and thereby brings down the cost and time of the experiment. A large electric current gives large electric loading of the jets, with resulting large electric body forces modifying the fluid mechanics. It is important to retain this feature, since it will confront us in most Ruhnke-Gourdine variations, one known partial exception being the Latham approach. For moderate crosswinds, the dominant demand for large jet momentum flux per unit of length along the jet row comes from the requirement to control the electric canopy curvature, which is an electric loading effect. Ground corona would destroy the physical simplicity needed to be able to learn from the cost- and time-limited experiment. Restriction to small fields which do not draw a corona from the ground, together with the large electric loading requirement, would force a scaledown of the experiment in which important turbulence features of the atmospheric boundary layer would get lost. Therefore, it is attractive to do the experiment over water, such that large fields are possible without drawing a corona. A small lake exposed to a shore wind would be suitable. Measurements should include local air velocities, electric fields, and space charge densities. If designed properly, the experiment will clarify: [1] the effect which atmospheric turbulence has on the upward and other distribution of the seeds, [2] the interaction of the jets with each other, [3] the interaction of the jets with the atmospheric boundary layer and wind, with emphasis on downstream states and the state underneath the jets, and [4] the electric loading effects on the jets, which can be investigated from experiments performed with and without electric current in the jets. No fog is necessary. The effects of seed slippage are well understood, and therefore their absense due to the choice of low mobility does not spoil the experiment in regard to interpretability. The experiment has further utility in demonstrating that large electric fields can indeed be set up by suitable arrangement. Experiment details can be worked out in a collaborative effort.

In view of the pressing time table, we should get started with the sketched one-year activity as soon as possible. After selection of the best Ruhnke-Gourdine variation has been made, plans can be drawn up for further development and field testing. If things are done sensibly, the field test can be set up in the second year.

15. Statement by James Jiusto

WARM FOG MODIFICATION - ELECTRICAL CONCEPTS

by James E. Jiusto

1.0 Background

As is well known, supercooled fog (<0°C) often can be dispersed by seeding with dry ice, AgI, or liquid propane. Warm fog dispersal is extremely difficult in that one cannot take advantage of a colloidal instability such as exists in supercooled fogs (i.e., difference in vapor pressure between water and ice). Hence one typically must resort to "brute force" methods and attempt to make them as efficient as possible.

Houghton and Radford (1938) achieved modest success on a very small scale with a hygroscopic-solution seeding technique. Four decades of searching for a better method have followed, making use of virtually all reasonable physical principles. [Note reviews of Junge, 1958; Jiusto, 1964: Silverman and Weinstein, 1974.]

Some of the conclusions that might be reached are as follows:

a. One should not expect to discover colloidal instabilities or "free energy" sources that can be exploited in warm fog modification.

b. Less efficient methods, however, should not summarily be ruled out, particularly in view of the greater dollar losses associated with rerouting of larger aircraft, higher airport traffic densities, increased fuel costs, etc. Occasional aircraft crashes in fog clearly are more devastating today and the human factor cannot be measured in monetary terms.

c. Though not a panacea, the thermal-kinetic concept of clearing warm fog is probably the best method that exists today. It has been tested extensively (from FIDO days on) and is in operational use in France. As the FAA estimated, such a system could be cost effective in Los Angeles, CA; and I would estimate at five to ten other high density-high fog occurrence airports in the country.

d. One cannot expect a system that will effectively modify 100% of warm fogs; 90% is probably optimistic. However, even a 70 to 80% capability for increasing visual range to CAT I or CAT II conditions would probably justify itself.

e. Because all warm fog modification concepts are marginal, one might consider combining two or more schemes for higher efficiency.

f. A modification concept generally looks much better on paper (and in the lab) than it proves in the field. Inherent system inefficiencies in adverse conditions and the atmosphere's seeming tendency to adjust to perturbations appear unavoidable. Experience in many weather modification projects suggests that after you've calculated the amount of energy or seeding material seemingly needed, multiply roughly by one order of magnitude.

g. The critical airport volume to be modified, $\sim 10^7$ m^3 to a height of about 60 m (as discussed at the Workshop), is valid. This volume and its movement with wind speed can prove awesome; early realistic scaling of laboratory or small field tests is essential.

h. There is no substitute for a step-by-step development of a technique: initial promising calculations; lab or chamber tests; some numerical modeling if possible; a limited field test; and finally a large scale field test. Many concepts fall by the wayside before reaching the last and most costly stage.

2.0 Electrical Fog Dispersal

Over the years a number of investigators have considered electrical methods of "clearing" (i.e., improving RVR in) fog. None have proved practical to date, but some might argue a lack of sufficiently sustained and comprehensive effort along these lines. At our recent Workshop the mechanisms proposed seemed to fall into four categories:

a. Electrical precipitation of fog drops in strong electrical fields created by charged particles from ground generators.

b. Like a. above but category supplemented by some generators putting out small particles of the opposite sign with higher mobility. In this category, and possibly a., it was stated that electrical coalescence of fog drops might augment electrical precipitation.

c. Use of much bigger charging generators to entrain substantial ambient fog drops, charge them, and promote clearing.

d. Seeding the fog with large charged water drops ($\sim$ 30 - 60 μm or so) to enhance droplet coalescence and fallout.

Items c. and d. were only briefly introduced at the Workshop and hence details are lacking. Charged-drop seeding to enhance coalescence (item d.) has been considered by some investigators over the years, with less than satisfactory results. Smith's (1976) encouraging laboratory results with 66 - 116 μm radius drops yielded enhanced collection efficiencies of $\sim$ 25, though he pointed out possible difficulties in applying the concept to field conditions. Tag (1977) modeled the charged-drop concept, using what appeared to be realistic fog and seed conditions. His conclusion was:

"Unless charges and seeding concentrations can be very greatly increased, charged drop seeding is probably not a viable dissipation technique." Also, he found that the optimum size for charged drops was 10 - 15 μm radius, and that the natural fog drop sizes were important. The efficient generation of a narrow size distribution of water drops on a large scale is a formidable engineering task.

The air entrainment implied in category c. suggests passing a significant portion (say $\gtrsim$ 10%) of the 10^7 m^3 of fog through the large generators. Past attempts to "process" fog air by passing it through a heater or de-humidifier (e.g., Houghton and Radford, 1938) quickly revealed enormous energy requirements and lack of feasibility for airports.

This is not to say that categories c. and d. could not be useful as a supplementary benefit to related concepts.

3.0 Electrical Precipitation of Fog

Categories 2a and 2b -- referred to as electrical fog precipitation though some droplet coalescence may take place -- was the main focus of the Workshop. NASA has supported fairly extensive research in this area as indicated by Contractor Reports 3255, 3440, 3481 and 3654. (The first two reports were available prior to the Workshop.) W. Frost, Principal Investigator, has actively investigated and amplified on the concept introduced initially by M. Gourdine.

Qualitatively, the concept has appeal in that it reportedly circumvents the high energy requirements of other electrical methods. However, it is not clear as yet that the system objectives can be achieved. Convincing calculations and small-scale fog modification tests are lacking.

The following comments pertain to the suggested topic outline of V. Keller (NASA) on system considerations.

a. Particle Generation

The concept is predicated on the generation of large concentrations of submicron charged droplets -- $\sim$ 0.1 μm radius. From the initial stagnation pressure of 43.6 psia and 100% RH (Collins et al., 1981, NASA CR 3481), one can assume that homogeneous condensation and condensation on ions will take place in the expansion cone of the generator. Classical nucleation theory (pure water) predicts that at saturation ratios $\gtrsim$ 4-5, drops of order 0.1 μm radius and concentrations $\lesssim 10^{10}$ cm^{-3} should result. Recent theoretical and experimental work proves that this is not likely because of rapid particle agglomeration (Kantola, 1982). For what appear to be related conditions, Kantola (G.E. Labs) measured particle sizes of ∿ 1.0 μm and concentrations of ∿ 10^6 cm^{-3}. In the presence of corona, L. Ruhnke reported particle size of ∿ 4 μm, which appears consistent with the G.E. work.

Thus, NASA (and subcontractors) should evaluate the impact of an order-of-magnitude larger charged droplets on the concept. Also a lower concentration of charged droplets (values not explicitly stated to my knowledge) should be considered.

Following the generation of these submicron to few micron size droplets, how long will they persist? Report CR 3255 (page 36, Christensen and Frost, 1980) indicates that because of fog humidities of ∿ 100% RH, evaporation will "probably not significantly decrease the size and number of particles." The Kelvin curvature effect will result in rapid droplet evaporation! Consider any of the well known droplet growth (evaporation) equations, e.g.:

$$r \frac{dr}{dt} = G \left(S - \frac{a}{r} + \frac{b}{r^3}\right) \qquad (1)\ \text{Fletcher (1966)}$$

$$\text{Where } G = \frac{D\rho_v}{\rho_v} \left[1 + \frac{DL^2\rho_v Mo}{RT^2 k}\right]^{-1} \qquad (2)$$

a/r = Kelvin curvature term and $a \approx \frac{3.3 \times 10^{-5}}{T}$ (cm)

b/r^3 = soluble nucleus term = 0 (pure water)

S = supersaturation $\approx$ 0 in fog.

Consequently in this case (neglecting ventilation effects and accommodation and condensation coefficients ≠ 1), equation (1) reduces to:

$$t = \frac{r^3 - r_o^3}{3Ga} \qquad (3)$$

Thus the evaporation time t for pure water droplets of radius r at RH = 100% is approximately:

t	r
2.7 x 10^{-3} sec	0.1 μm
2.7 sec	1.0 μm

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With a stated generator exit velocity of 300 m/sec (diminishing rapidly downstream), 0.1 μm radius drops would evaporate within the first meter; 1.0 μm drops would rise considerably higher but still evaporate before the maximum desired height is reached. This raises a number of interesting questions:

(1) Will the resultant "ion clusters" still be suitable?

(2) Should "dirty" water (e.g., saline drops) be used to retard evaporation?

(3) Would sub-micron aerosol particles of low volatility be better and how should they be generated? (Note that Vonnegut, 1956, employed charged oil smoke particles in a fog modification experiment.)

b. Injection into the Atmosphere

A 60 m altitude of fog clearing would probably be a realistic and sufficient depth for most airport operations. It roughly corresponds to the CAT II landing requirement of 68 m at the approach marker; perhaps only 25 - 30 m would be needed in the runway zone. The FAA should be consulted on these points. A different and possibly shallower clearing zone requirement would be appropriate for ships navigating the Panama Canal.

If the initial grounding of high mobility seeds is minimized, as seems possible, the charged particles should achieve altitudes dictated by the momentum or kinetic energy of the generator jet. It takes a powerful energy source to reach 60 m. Reliance apparently is being placed on turbulence to reach high levels, although the term seemed to convey two meanings at the Workshop.

One interpretation seemed to be turbulent transport induced by repulsion of like charges with an almost unlimited altitude capability. Because electrical forces are short-range, I suspect this idea bears further clarification and perhaps measurement verification.

Regular atmospheric turbulence is reasonably well understood and would diffuse charged particles both laterally and vertically. Unfortunately in fogs, inversions are normally present which would limit thermal buoyancy and upward transport. Most advection fogs involve the passage of warm air over a cold moist surface -- sustained inversion conditions.

Radiation fogs commence with very strong thermal stability. However, as dense fog ($\gtrsim 0.2$ g/m^3) develops, the level of net radiational cooling shifts to the fog top. Concurrently, heat flux from the soil warms the surface layer and very unstable (neutral to superadiabatic) lapse rates can develop. At this point turbulent mixing to higher levels should be helpful. Figure 1 illustrates the nocturnal transition in atmospheric stability that takes place in the boundary layer during a dense radiation fog.

c. Charge Attachment to Fog Drops and Rate of Precipitation

These are critical topics for which good estimates, supporting calculations, and preliminary verification tests in a chamber appear appropriate. One can appreciate that the set of equations involved may be non-linear; that a full numerical modeling effort would be formidable; and undoubtedly premature since many of the key input variables are poorly known or debatable.

However, it would seem that a number of "what-if" calculations can be made (subject to revision) that would be very helpful, e.g.:

(1) Assuming that seed drops of radii 0.1, 1.0, and 10 μm are generated in varying concentrations N_s, at what rate and/or how many will attach to neutral fog drops of size d_f and concentration N_f?

(2) If an electric field of 10^4, 10^5, or 10^6 v/m can be created over altitude h, how rapidly will the above fog drops precipitate out?

(3) For given initial fog densities (LWC = 0.1 - 0.5 g/m^3) and visual ranges of say 50 - 400 m, what changes in these initial fog variables might result?

(4) How long will it take? This matter, the time constant, once simply expressed at the Workshop ($\tau = H/E_{max} \cdot k$), immediately provided much insight into system needs and feasibility.

Perhaps the Principal Investigators have already performed such calculations and time precluded their discussion. If not, these kinds of working calculations should be undertaken soon.

d. Rate of Advection of Fog into Cleared Area

Fogs rarely occur in dead calm conditions. When so indicated, it usually means that the response threshold of the typical airport or NWS anemometer is $\gtrsim$ 1 mph ($\sim$ 0.5 m/sec).

In numerous inland radiation fogs at Albany, NY, we typically measure horizontal winds of: $\sim$ 0.5 - 1.5 m/sec at 4 - 16 m (mast anemometers) and $\sim$ 1 - 3 m/sec at 25 - 50 m (tethered balloon sensors). I would estimate typical winds in advection fogs of roughly twice those values above. Other estimates can be obtained from the AFGL and the FAA, who have examined considerable wind data in coastal advection fogs.

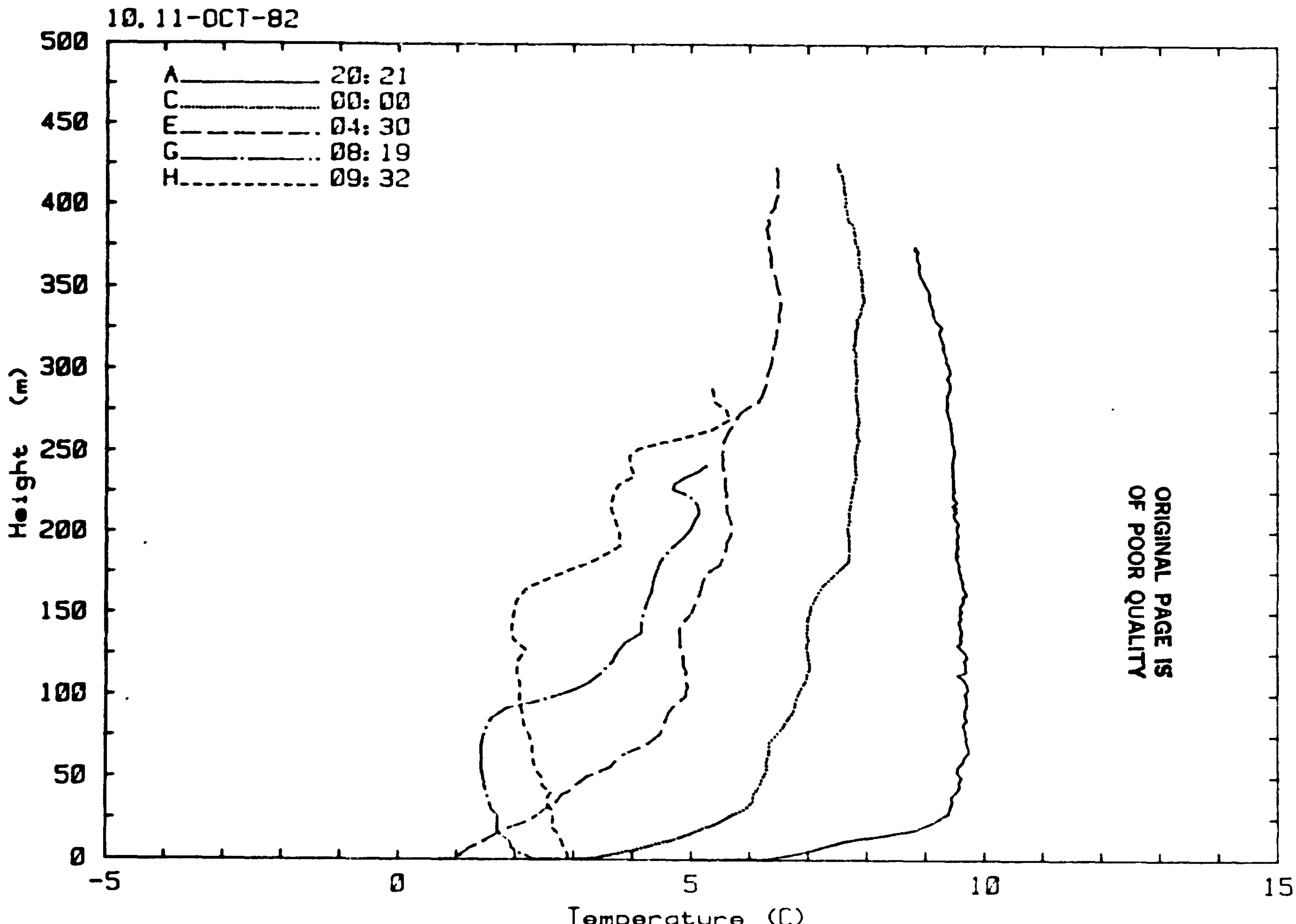

Fig. 1. Temperature Profiles with the Tethersonde (10-11 Oct 1982)
(Jiusto and Lala, 1983)

There are usually preferred wind directions for fogs in given locations. Wind roses (available or compiled from NWS data) would indicate direction and speed frequencies and dictate deployment strategies for fog modification devices.

e. Other Comments - Field Tests

The maximum field strength achievable is a critical variable that is open to question. In our SUNY fog chamber tests for the FAA of the Gourdine system, we measured surface fields of order 10^4 V/m (Jiusto, 1972). Proximity to metal walls (26 x 25 x 22 ft. chamber) quite likely grounded some of the space charge, as was noted. Thus the reported fields by M. Gourdine of $\sim 10^5$ V/m in Panama appear reasonable. The measured Panama values as reproduced in Christensen and Frost, 1980, indicated surface fields of $\sim 2 - 3 \times 10^5$ V/m within 6 ft. of a generator and $\sim 1.5 - 4 \times 10^4$ V/m (similar to SUNY values) between generators. There is little reason to doubt these measurements. Associated visibility changes, if any, were unconvincing.

To achieve fields of $\geq 10^6$ V/m, which was once proposed, seems optimistic. Such values are equivalent to thunderstorm breakdown fields, while corona discharge from surface objects or vegetation would undoubtedly inhibit such field strengths. In any event, the newer prototype generator can be tested to check this issue.

Further consideration leads me to believe that much can be learned about the concept from some well-designed large chamber tests. Several large environmental chambers exist (NASA, Eglin AFB, GE-Pittsfield, etc.) where wall effects should be acceptably small. As a minimum one could conceivably clarify generator output characteristics in a still environment. Two types of experiments might be considered:

(1) Humid but noncondensing environment of 90 - 99% RH. Goals to include measured charged particle sizes aloft, their number concentration, space charge aloft vs. height, and surface field strength.

(2) Fog Environment - RH $\geq$ 100%. Some of the above goals plus measurements vs. time of fog liquid water content, visual range, and fog drop spectra.

Figures 2 through 4 illustrate some fog characterization tests recently performed (Jiusto et al., 1982) in the G.E. Pittsfield fog chamber (11,400 m^3 volume; cylinder 24.4 m dia. by 24.4 m high). Data were continuously acquired via a computerized DEC system with the key sensors (Table 1) on an elevated movable platform.

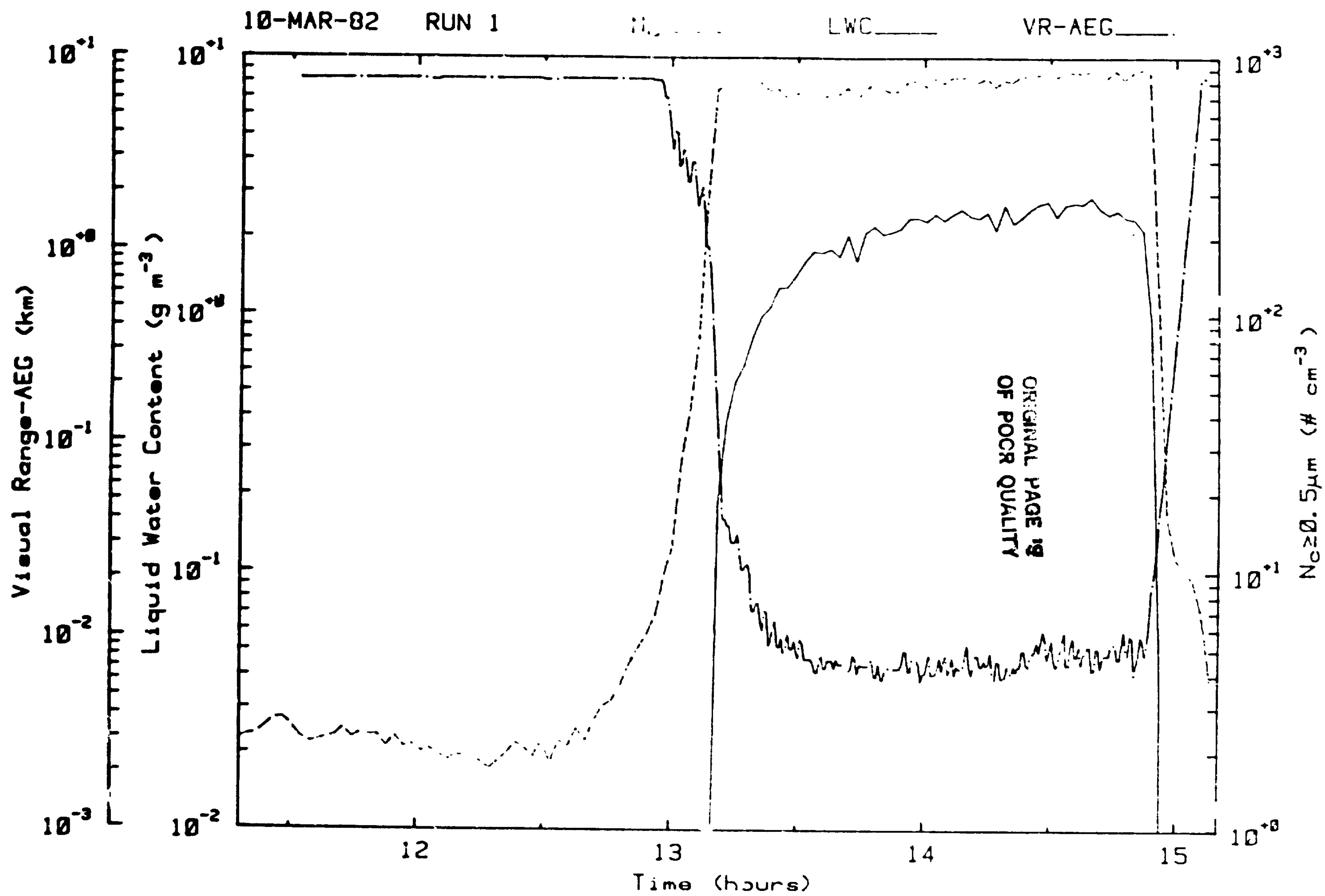

Figure 2. Fog physics variables vs. time
(Jiusto et al., 1982)

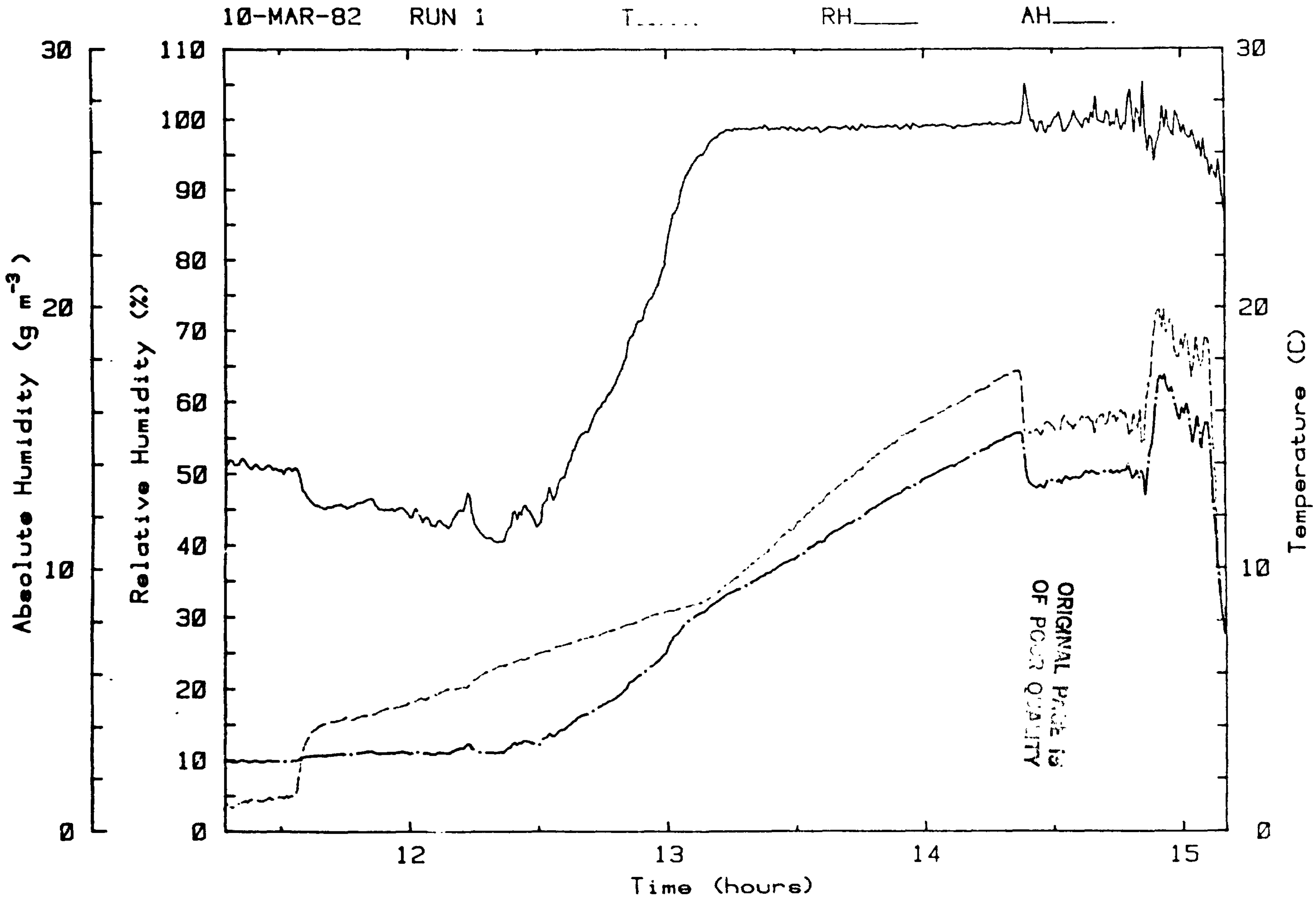

Figure 3. Fog thermodynamics variables vs. time (Jiusto et al., 1982)

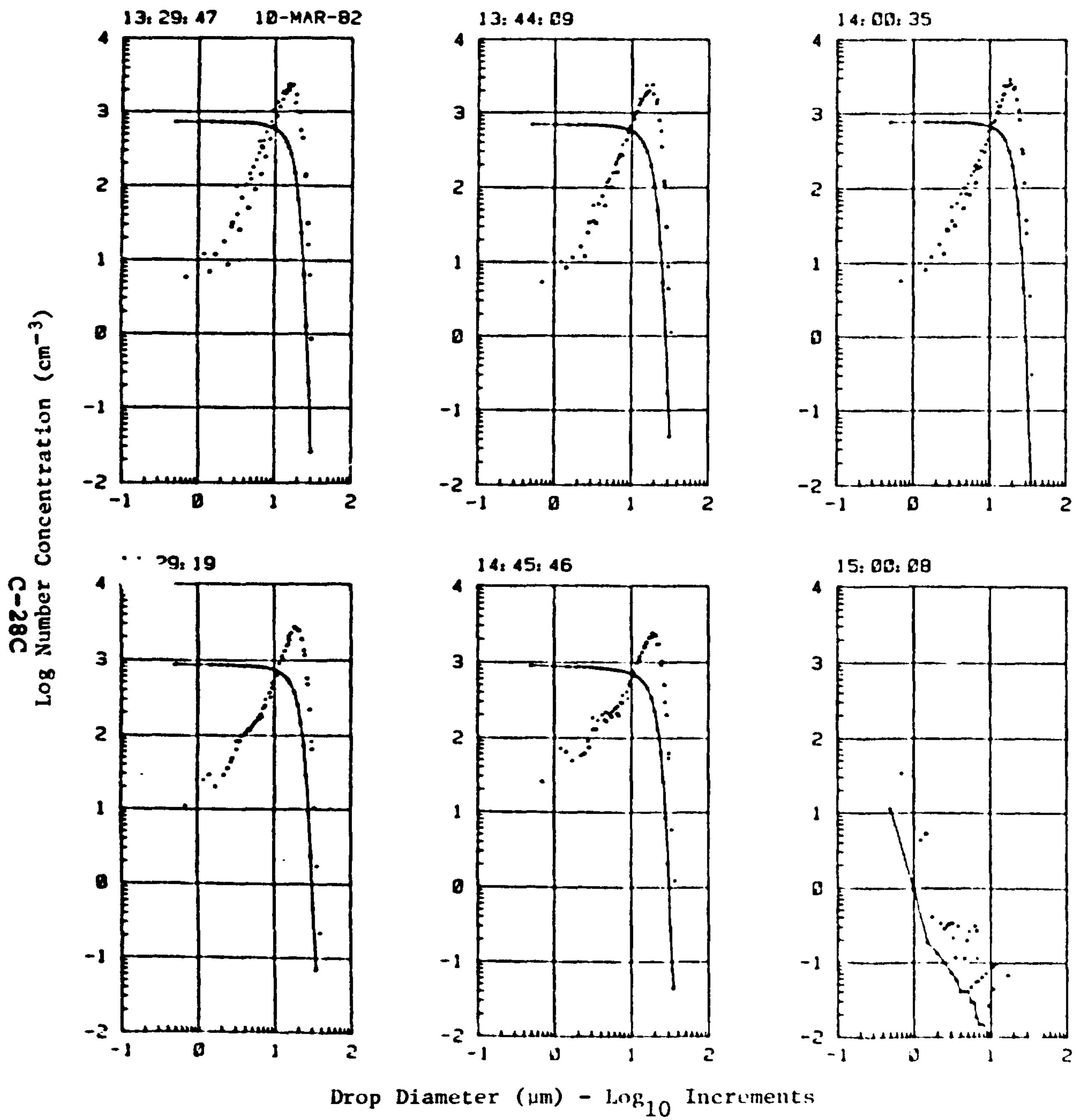

Figure 4. Drop size distributions (FSSP-100) - Run 1. (Solid curve - cumulative number concentration; Points - differential concentration of drops, dN/d log D.) (Jiusto et al., 1982)

Table 1. Fog Property Measurements

	Instrument	Variables	Sample Rate
a.	Optical forward scattering probe - P.M.S. Model FSSP-100 (0.5 - 47 μm dia. size range)	Drop sizes, number concentration Nc, liquid water content (LWC), and computed visual range (V.R.)	Continuous 2 min. averages
b.	ASRC/SUNY field psychrometer	Temperature, relative humidity (RH), absolute humidity (AH)	30 sec.
c.	AEG-Telefunken scattered light meter	Visual range (V.R.)	30 sec.
d.	Small particle detector (Gardner)	Aerosol (condensation nucleus) concentration	Periodic
e.	Modified Hi-Vol sampler	Liquid water content	Periodic

Definitive fog-classification experiments were conducted over an intensive 2½ day period. These data are merely cited to indicate the kinds of relevant cloud physics and thermodynamic information that readily can be obtained. (Other groups have similar capability.) Coupled with appropriate atmospheric electricity sensors, a number of questions pertaining to the fog dispersal concept could be addressed. Better input values for calculations and models should result.

A next logical step might be a limited field program, assuming the concept was still deemed feasible. The argument that only a full-scale field program will do is questionable. This is not the normal course in weather modification. As indicated earlier, better results are typically obtained in smaller volumes where "overkill" energies can be applied. In terms of adverse boundary effects in the field, one can note from the Panama Canal tests (cited in Christensen and Frost, 1980, p. 40) that measured electric field conditions were virtually no different in the center of the 16 generator grid than with any 4 generators along the array boundary. Some reasonable scaling would appear possible.

In terms of appropriate fog field measurements, careful site selection and program design are essential. More extensive instrumentation than that indicated for chamber tests would be required. Additional information on fog field program methodology, current instrumentation, and fog characteristics is available (e.g., Roach et al., 1976; Pilié et al., 1975; Jiusto and Lala, 1980 and 1983).

4.0 Concluding Comments and Suggestions

Workshop participants had a very short time to consider and evaluate the electrical fog modification concepts presented, and only limited access to NASA Contractor Reports on the subject. Thus opinions stated herein should be viewed accordingly.

a. The number of differing approaches and views suggested by individuals expert in the area of atmospheric electricity were considerable. For the electrical precipitation concept, additional calculations and estimates of some of the key variables mentioned (Section 3.0) would be in order. With physical processes clearly enumerated and some supporting numbers, perhaps a higher level of consensus might be reached.

b. The electrical precipitation mechanism has been the thrust of NASA's interest in recent years. It appears that some solid work has been done by W. Frost and Associates. It seems reasonable to take the next logical steps to determine its feasibility for fog clearance. One should recognize that the odds are long for unequivocal success, but that might be said for most weather modification activities.

c. In my judgement, these next steps should include:

(1) Explicit identification of the various physical processes involved, with supporting calculations and best-estimate values for key variables at each step in the chain of events hypothesized.

(2) A test of the charged particle generation in a suitably large chamber under humid but nonfogging conditions (RH of $\sim$ 90 - 99%). Emphasis would focus on measurements such as charged particle sizes, number concentrations, space charge, and surface field strengths.

(3) Tests in the same large chamber with fog present to measure the above variables and also the degree of modification of fog water content, fog drop spectra, and visual range.

(4) The design and execution of a fog field program of modest scale, depending upon the results of steps 1 - 3.

d. It is rather obvious that this complex topic crosses many disciplines including: atmospheric electricity, engineering, aeronautics, boundary layer meteorology and cloud physics. NASA might well consider some continuing mechanism for constructive inputs to and evaluation of the program concept as it progesses.

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